

OFFICE OF NAVAL RESEARCH

FINAL REPORT

for

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**Title: Fundamental Models of Selective Laser
Sintering of Metal Powders**

PI: Yuwen Zhang, Ph.D.

Department of Mechanical and Aerospace Engineering
University of Missouri-Columbia
E 3411 Thomas & Nell Lafferre Hall
Columbia, MO 65211
Tel: (573) 884-6936
Fax: (573) 884-5090
zhangyu@missouri.edu
<http://www.missouri.edu/~zhangyu>

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Program Officers: Dr. Ralph Wachter, ONR 361, Office of Naval Research, 875 N. Randolph St., One Liberty Center, Arlington, VA 22203-1995
Dr. Khershed P. Cooper, US Naval Research Laboratory, Code 6325, 4555 Overlook Avenue, SW, Washington, DC 20375-5343

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1. Productivity Measures

- Number of book published: 1
- Number of refereed journal articles: 14
- Number of articles in Conference Proceedings: 12
- Number of refereed papers submitted/to be submitted: 5
- Number of graduate students supported: 4

2. Summary of Research Tasks

- Absorptivity of Laser Radiation by Metal Powders
 - Temperature and wavelength-dependent spectral absorptivities for some important metallic materials in the infrared were studied.
- Modeling of SLS of Two-Component Metal Powders
 - Analytical models of melting and resolidification of powder bed under constant or temporal Gaussian heat source were developed.
 - Two-dimensional models for melting accompanied by shrinkage and resolidification were developed and parametric studies were performed.
 - Three-dimensional models for SLS of two-component metal powders were developed by accounting for melting, shrinkage, capillary flow, and resolidification.
- Modeling of SLS of Single-Component Metal Powders
 - Analytical model of melting of powder bed under constant heat source were developed.
 - Three-dimensional model for SLS of single-component metal powders were developed by considering partial melting, shrinkage, capillary flow, and resolidification.
 - Three-dimensional model for Selective Laser Powder Remelting (SLPR) of single-component metal powders were developed by solving melting with shrinkage, resolidification, as well as convection in the liquid pool.
- Modeling of Post-Processing of the Laser Sintered Porous Part
 - A model for liquid metal in filtration and solidification during post-processing of laser sintered porous part is developed.

3. Detailed Summary of Technical Progress

The project involves fundamental modeling of the laser beam-material interactions associated with Selective Laser Sintering (SLS) of single- and two-component metal powders, as well as post-processing of the sintered parts with liquid metal infiltration.

3.1 Absorptivity of Laser Radiation by Metal Powders

Any model for laser processing of materials must have a complete description of the coupling between the laser source and the material. The coupling is defined by the spectral absorptivity of the material at the wavelength of operation; hence the normal spectral absorptivity is a critical parameter of interest. Optical properties of bulk metals are typically functions of wavelength, temperature, surface geometry (roughness), incident intensity, and physical atomic structural and

electrical properties of the material. Since absorptivity is dependent on temperature, it is also important to consider the absorptivity change in the modeling of laser heating.

Temperature and wavelength-dependent spectral absorptivities for some important metallic materials in the infrared were studied by Boyden and Zhang [J3, C7]*. For the application of laser material processing, temperature-dependent values are calculated based on available experimental data. Figure 1 shows the comparison of the predicted absorptivity of AISI 304 stainless steel as a function of wavelength with available experimental data in the literature. The calculated absorptivity of the major component in AISI 304 – Fe is also shown in Fig. 1. The absorptivity of AISI 304 is much higher than that of pure iron metal. It can be seen that our calculated results agreed very well with the experimental data. The optical constants and absorptivity of other element (Al, Cu, and Ni) and alloys (Inconel, A-110-AT, Al 2024, Al 7075, and TiB120 VAC) are also calculated based on the Drude type model. The predicted absorptivities of the pure metals at 10.6 μm agreed very well with the experimental results except for the transition metals due to interband absorption. Agreement of alloy and element absorptivity calculated values and the experimental data is good at 10.6 μm but not at 1.06 μm . The higher absorption at 1.06 μm can be contributed to parallel band absorption, which is not included in the Drude absorption theory.

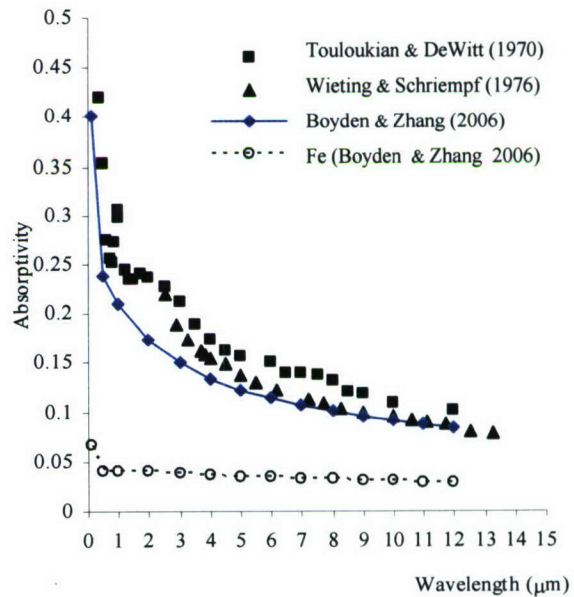


Figure 1 Wavelength-dependent absorptivity for AISI 304 stainless steel [J3]

3.2 Modeling of SLS of Two-Component Metal Powders

Analytical models of melting and resolidification of powder bed.

Melting and resolidification in SLS of two-component metal powders in SLS processes were systematically investigated by the PI and students. Melting of a subcooled powder bed with the *finite thickness* that contains a mixture of two metal powders with significantly different melting points is investigated analytically [J6, C1]. Shrinkage induced by melting is taken into account in the physical model. The effects of porosity, Stefan number, and subcooling on the surface temperature and solid-liquid interface are also investigated.

In order to discover the advantages of utilizing a pulsed laser in a SLS process, melting and resolidification of a subcooled two-component metal powder bed with a temporal Gaussian heat flux was investigated analytically by Konrad *et al.* [J11]. The laser-powder bed interaction can be divided into three stages: (1) preheating, (2) melting with shrinkage, and (3) resolidification; their solutions were obtained by using an integral approximate solution. The results show that an increase in heat source intensity or powder bed porosity will result in an increase of the melt pool depth, surface temperature, and overall processing time.

* See lists of journal and conference papers.

Two-Dimensional Modeling of SLS of Two-Component Metal Powders

SLS of the first layer is modeled as melting and resolidification of a metal powder layer subject to a moving heat source on top while the bottom is adiabatic [J1, C3]. SLS of the consecutive layer is modeled as melting and resolidification of a metal powder layer on top of the existing multiple resolidified layers [J1, C2]. The results indicate that the thicknesses of the loose metal powder layer, the moving heat source intensity and the scanning velocity have significant effects on the sintering process in both the first layer and each subsequent layer. A parametric study is performed and the best combination of processing parameters is recommended.

Three-Dimensional Modeling of SLS of Two-Component Metal Powders

The highest level of our efforts is represented by modeling of three-dimensional SLS process with both shrinkage and liquid flow considered [J4-5, J9-10, C6, C9-11]. Laser sintering of a two-component metal powder layer under a moving Gaussian laser beam was investigated numerically by Chen and Zhang [J4, C6, C10]. The laser induced melting with shrinkage, and resolidification of the metal powder layer are modeled using a temperature transforming model. The liquid flow of the melted low melting point metal driven by capillary and gravitational forces is also taken into account. Simulations were conducted using a mixture of 40% nickel braze powder and 60% AISI 1018 carbon steel powder by volume. To validate the simulation results, the results of numerical solution are compared with the experimental results as shown in Fig. 2. The black area in the micrograph is a local void and the light area is sintered metal. It can be seen that the actual and predicted shapes of the Heat Affected Zone (HAZ) are similar, but large degree of local porosity exists in the experimentally observed HAZ; this indicates that the HAZ in the experiments are not fully densified as we assumed. Therefore, a partial shrinkage model was developed to allow part of the gas remains in the HAZ [J5]. The results showed that the predicted results agreed very well with experiments if it is assumed that the volume fraction of the gas in the HAZ is 0.2.

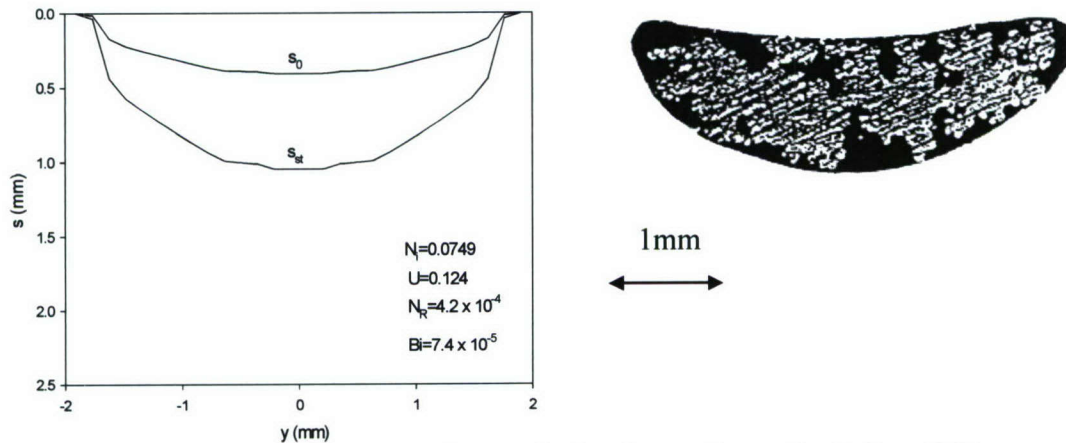


Figure 2 Comparison of numerical and experimental solutions [J4]

In reality, SLS is a layer-by-layer process by which the sintering process occurs in a fresh loose powder layer on top of multiple sintered layers. Numerical solution of three-dimensional laser sintering of a two-component metal powder layer on the top of multiple sintered layers was investigated for the case of single-line scanning [J9, C9, C10] and multiple-line scanning [J10,

C10-11]. The modeling of single-line scanning addresses laser scanning in the middle of the loose powder on top of the existing sintered layers, and the multiple line scanning is modeled as sintering at the boundary of loose powder layer and sintered layer as shown in Fig. 3; these treatment are reasonable because the diameter of the laser beam is much smaller than the sizes of the powder bed in the horizontal direction, and the effect of laser heating is limited in the region very close to the laser spot.

Figure 4 shows the simulated results for the single line scanning – which results in axisymmetric HAZ about $Y=0$ and only half ($Y>0$) of it is shown – and multiple-line laser scanning – the HAZ is no longer axisymmetric. The volume fractions of the gas remaining in the HAZ for both cases were $\varphi_{g,\ell} = 0.2$, which is reduced from 0.42 in the loose powder.

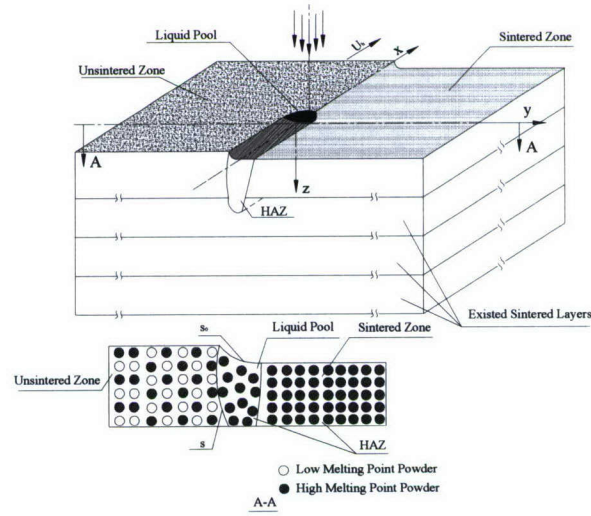


Figure 3 Physical model of SLS by multiple-line laser scanning [J10]

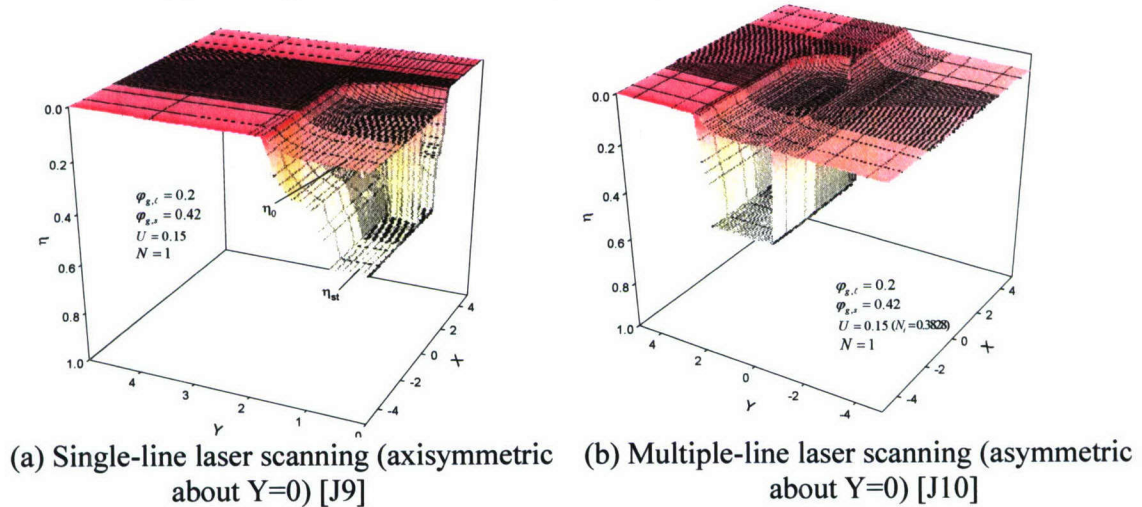


Figure 4 Three-dimensional shape of the HAZ ($\varphi_{g,\ell} = 0.2$)

3.3 Modeling of SLS of Single-Component Metal Powders

Analytical models of partial melting of powder bed

The final product of SLS of the two-component powder exhibits the mechanical properties and characteristics of their weaker component; therefore, the interest in the production of metallic objects using single component powders has been increased in the recent years. One approach is to employ partial melting, in which only the surfaces of particles are molten and the powders are sintered by binding the non-melted solid cores. Since SLS is a very rapid process, the liquid layer and solid core of a partially molten powder particle are not at thermal equilibrium and have different temperatures. The *mean temperature* of a partially molten grain can be either below or above the melting point depending on the degree of melting. Thus, the melting process can be assumed to occur in a temperature range and the degree of melting is function of temperature in the range. Partial melting of a single-component metal powder with constant heat flux was investigated analytically by Xiao and Zhang [J13, C5]. The partial melting model was also extended to melting of alloy by including a completely-melted liquid layer on top of the mushy zone [J14].

Three-dimensional model for SLS via partial melting

Xiao and Zhang [J7, C8] numerically solved three-dimensional partial melting of a single-component metal powder bed subject to a moving Gaussian laser beam. The liquid velocities induced by capillarity and gravitational forces and solid velocities caused by shrinkage during the melting process were taken into account. Numerical calculations were performed for sintering of AISI 304 stainless steel powder. In order to minimize the balling effect and geometric distortion (curling or delaminating), a pre-heated powder bed with initial temperature of 380°C was used in the simulation. Figure 5 illustrates the surface temperature distribution of the powder bed. It can be seen that the peak temperature at the powder bed surface is near the trailing edge of the laser beam rather than at the center of the laser beam due to motion of the laser beam. Figure 6 shows the three-dimensional shape of the powder bed surface, molten pool and HAZ at the same condition of Fig. 5. The shrinkage at the track of the center of the laser beam is most significant and a groove is formed on the surface of the powder bed.

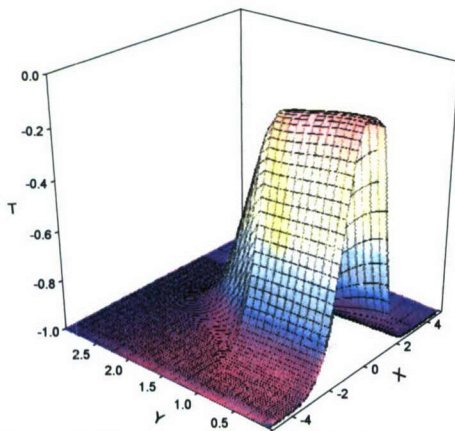


Figure 5 Temperature distribution on the powder bed surface ($N_i = 0.19, U_b = 0.12$) [J7]

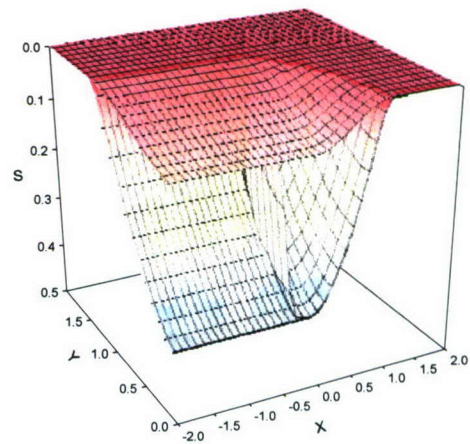


Figure 6 Three-dimensional shape of the HAZ ($N_i = 0.19, U_b = 0.12$) [J7]

Three-dimensional models for Selective Laser Powder Remelting (SLPR)

Modeling of SLS of single-component metal powder through complete melting – an approach to fabricate *fully-densified* single component part – is also performed. Liquid flow occurs in a non-porous liquid pool, and the effect of liquid flow driven by the surface tension gradient and gravitational force on the SLS process is much stronger. The Darcy's law that was used to obtain the liquid velocity for the case of partial melting is no longer applicable and the convection in the liquid pool must be described by the complete three-dimensional Navier-Stokes equations. A three-dimensional model describing melting and resolidification of direct metal laser sintering process under the irradiation of a moving Gaussian laser beam is developed by Xiao and Zhang [J12]. We also developed a three dimensional model describing melting and resolidification of direct metal laser sintering of loose powders on top of sintered layers with both single- [C12, S1] and multiple-line laser scanning [S3]. Effects of shrinkage and natural convection driven by the surface tension and buoyancy force are taken into account. The energy equation is formulated using temperature transforming model and solved by the finite volume method. Temperature distribution and velocity field are investigated. The results show that increasing initial porosity of the powder bed enlarges the depth of the melt/solid interface and laser intensity has great influence in both depth and width of the liquid pool.

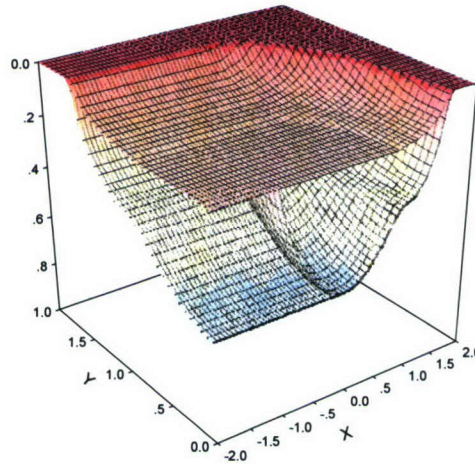


Figure 7 Three-dimensional shape of the HAZ ($\Delta_s = 0.4, U_b = 0.02, \varepsilon = 0.5, N = 5$) [C12]

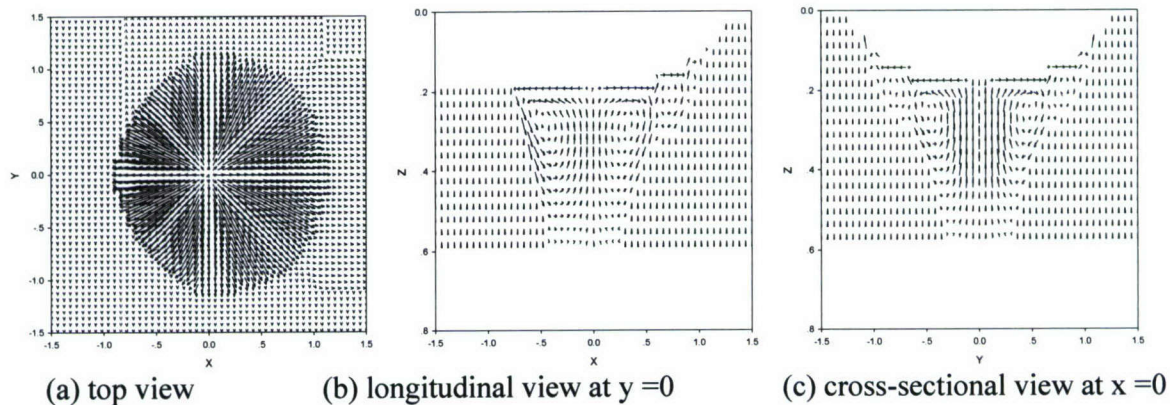


Figure 8 Dimensionless velocity vector plot ($\Delta_s = 0.4, U_b = 0.02, \varepsilon = 0.5, N = 5$) [C12]

Figure 7 shows the three-dimensional shapes of the powder bed surface, melt pool and HAZ for single-line scanning with five sintered layers underneath ($N = 5$) and an initial porosity of 0.5 ($\varepsilon = 0.5$). The depths of surface and HAZ decrease with the increasing X in the laser scanning direction Y . Figure 8(a)-(c) show the velocity vectors in the liquid pool plotted in three different views. Since the surface tension is a decreasing function of temperature, i.e., $\partial\gamma/\partial T < 0$, the higher surface tension of the cooler liquid metal near the edge of the liquid pool tends to pull the liquid metal away from the center of the liquid pool, where the liquid metal is hotter and the surface tension is lower. Therefore, fluid flow on the surface of liquid pool is radially outward as can be seen in Fig. 8(a). The liquid metal flow is also driven by buoyancy force as illustrated in Fig. 8(b) and 8(c). The hotter liquid metal near the central region of the molten pool flows up to the surface, while the cooler liquid metal near the pool boundary sinks along the melt/solid interface to the bottom of the pool.

Figure 9(a)-(c) present the temperature contour in the powder bed plotted in three different views ($N = 5$). The Marangoni convection (radially outward) at the top surface and the shrinkage phenomenon resulted in a significant amount of heat flows from the hotter region to the colder region especially in the z direction, which in turn result in a wider and deeper melt pool. Another observation is that the isotherms near the melting front are more closely spaced compared with those far away from the melt/solid interface.

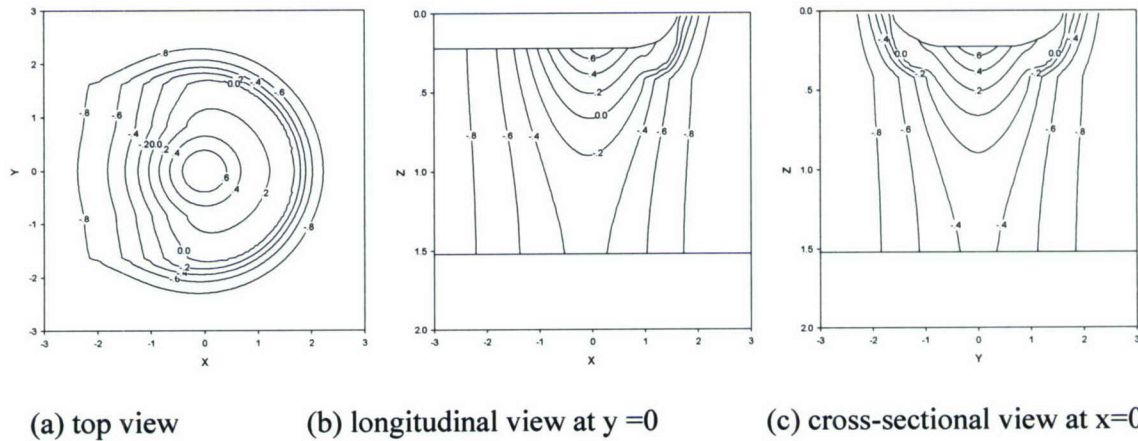


Figure 9 Dimensionless temperature contour ($\Delta_s = 0.4$, $U_b = 0.02$, $\varepsilon = 0.5$, $N = 5$) [C12]

3.4 Modeling of Post-Processing of the Laser Sintered Porous Part

The parts produced by SLS with single or multiple components powders are usually not fully densified and have porous structure. In order to produce fully densified part, post-processing is necessary. Compared to sintering and HIP processes, the advantage of infiltration is that the full density can be achieved *without shrinkage* in the post-processing. The additional advantages of post-processing with infiltration include: it is relative inexpensive, and tooling is similar to casting process. Infiltration is a process where a liquid metal is drawn into the pores of a solid (part produced by SLS of metal powder) by capillary forces. The liquid, as it advances through the solid, displaces vapor from the pores and leaves behind a relatively dense structure. The rate of infiltration is related to the viscosity and surface tension of the liquid, and the pore size of the SLS parts.

In order to understand the liquid flow associated with post-processing, a numerical study of transient fluid flow and heat transfer in a porous medium with partial heating and evaporation on the upper surface is performed [J8]. The dependence of saturation temperature on the pressure

was accounted for by using Clausius-Clapeyron equation. The results showed that as time passes the magnitude of velocity increases until the process reached steady state. Solidification of liquid copper infiltrated in steel skeleton was modeled using temperature transforming model in conjunction with Brinkmann model for liquid metal flow in porous media. The model was validated with the experimental data available in the literatures and parametric study was performed [S4]. Infiltration and solidification of liquid metal into laser sintered porous structure is modeled using Volume of Fluid (VOF) and temperature transforming model [S5]. The Ph.D. student (Piyasak Damronglerd) who is working on the modeling of post-processing is scheduled to graduate in Spring 2007 and is in the final stage of completion of his dissertation.

4. Book

- Faghri, A., and Zhang, Y., *Transport Phenomena in Multiphase Systems*, Copyright 2006 by Elsevier, 1064 pages, 403 illustrations, 292 problems and 62 examples, ISBN: 0-12-370610-6

5. Journal Papers

- J1. Chen, T., and Zhang, Y., 2004, "Numerical Simulation of Two-Dimensional Melting and Resolidification of a Two-Component Metal Powder Layer in Selective Laser Sintering Process," *Numerical Heat Transfer*, Part A, Vol. 46, No. 7, pp. 633-649, 2004.
- J2. Konrad, C., Zhang, Y., and Xiao, B., "Analysis of Melting and Resolidification in a Two-Component Metal Powder Bed Subjected to Temporal Gaussian Heat Flux," *Int. J. Heat Mass Transfer*, Vol. 48, No. 19-20, pp. 3932-3944, 2005.
- J3. Boyden, S., and Zhang, Y., "Temperature and Wavelength-Dependent Spectral Absorptivities of Metallic Materials in the Infrared," *AIAA J. Thermophysics and Heat Transfer*, Vol. 20, No.1, pp. 9-15, 2006.
- J4. Chen, T., and Zhang, Y., "Three-Dimensional Simulation of Selective Laser Sintering of a Two-Component Metal Powder Layer with Finite Thickness," *ASME J. Manufacturing Science and Engineering*, Vol. 128, No. 1, pp. 299-306, 2006.
- J5. Chen, T., and Zhang, Y., "A Partial Shrinkage Model for Selective Laser Sintering of a Two-Component Metal Powder Layer," *Int. J. Heat Mass Transfer*, Vol. 49, No. 7-8, pp. 1489-1493, 2006.
- J6. Chen, T., and Zhang, Y., "Analysis of Melting in a Subcooled Two-Component Metal Powder Layer with Constant Heat Flux," *Applied Thermal Engineering*, Vol. 26, No. 7, pp. 751-765, 2006.
- J7. Xiao, B., and Zhang, Y., "Partial Melting and Resolidification of Metal Powder in Selective Laser Sintering," *AIAA J. Thermophysics and Heat Transfer*, Vol. 20, No. 3, pp. 439-448, 2006.
- J8. Damronglerd, P., and Zhang, Y., "Transient Fluid Flow and Heat Transfer in a Porous Structure with Partial Heating and Evaporation on the Upper Surface," *Journal of Enhanced Heat Transfer*, Vol. 13, No. 1, pp. 53-64, 2006.
- J9. Chen, T., and Zhang, Y., "Three-Dimensional Modeling of Laser Sintering of a Two-Component Metal Powder Layer on Top of Sintered Layers," *ASME J. Manufacturing Science and Engineering*, Vol. 129, 2007, to appear.

- J10. Chen, T., and Zhang, Y., "Thermal Modeling of Laser Sintering of Two-Component Metal Powder on Top of Sintered Layers via Multi-line Scanning," *Applied Physics A: Materials Science & Processing*, Vol. 86, No. 2, pp. 213-220, 2007.
- J11. Konrad, C., Zhang, Y., and Shi, Y., "Melting and Resolidification of Subcooled Metal Powder Particle Subjected to Nanosecond Laser Heating," *International Journal of Heat and Mass Transfer*, Vol. 50, 2007, in press.
- J12. Xiao, B., and Zhang, Y., "Marangoni and Buoyancy Effects on Direct Metal Laser Sintering with a Moving Laser Beam," *Numerical Heat Transfer, Part A*, Vol. 51, 2007, in press.
- J13. Xiao, B., and Zhang, Y., "Analysis of Partial Melting in a Metal Powder Bed with Constant Heat Flux," *Heat Transfer Engineering*, Vol. 28, No. 5, 2007, in press.
- J14. Xiao, B., and Zhang, Y., "Analysis of Melting of Alloy Powder Bed with Constant Heat Flux," *International Journal of Heat and Mass Transfer*, Vol. 50, 2007, in press.

6. Papers in Conference Proceedings

- C1. Chen, T., and Zhang, Y., "Analysis of Melting in a Mixed Powder Bed with Finite Thickness Subjected to Constant Heat Flux Heating," *Proceeding of ASME Summer Heat Transfer Conference*, Las Vegas, NV, July 21-23, 2003.
- C2. Chen, T., and Zhang, Y., "Two-Dimensional Modeling of Sintering of a Two-Component Metal Powder Layer on Top of Multiple Sintered Layers with a Gaussian Heat Source," *Proceedings of 14th Solid Freeform Fabrication Symposium*, pp. 208-218, Austin, TX, Aug. 4-6, 2003 (Plenary Presentation).
- C3. Chen, T., and Zhang, Y., "Melting and Resolidification of a Two-Component Metal Powder Layer Heated by a Moving Gaussian Heat Source," *Proceedings of 2003 International Mechanical Engineering Congress and Exposition*, Washington, DC, Nov. 15-21, 2003.
- C4. Chen, T., and Zhang, Y., "A Parametric Study on Melting and Resolidification of a Two-Component Metal Powder Layer on Top of the Sintered Metal Layers," *Proceedings of 6th International Heat Transfer Symposium*, Beijing, China, June 15-19, 2004.
- C5. Xiao, B., and Zhang, Y., "Analysis of Melting in a Single-Component Metal Powder Bed Subject to Constant Heat Flux Heating," *Proceedings of 2004 ASME Heat Transfer/Fluid Engineering Summer Conference*, Charlotte, NC, July 11-15, 2004.
- C6. Chen, T., and Zhang, Y., "Three-Dimensional Simulation of Selective Laser Sintering of a Two-Component Metal Powder Layer with Finite Thickness," *2004 International Mechanical Engineering Congress and Exposition*, Anaheim, CA, Nov. 13-19, 2004.
- C7. Boyden, S., and Zhang, Y., "On Prediction of the Temperature Dependence Absorptivities of Pure Metal and Alloys at 1.06 μm and 10.6 μm ," *Proceedings of the 38th AIAA Thermophysics Conference*, Toronto, Canada, June 6-9, 2005.
- C8. Xiao, B., and Zhang, Y., "Partial Melting and Resolidification of Single-Component Metal Powder with a Moving Laser Beam," *Proceedings of 2005 ASME Summer Heat Transfer Conference*, San Francisco, CA, July 17-22, 2005.
- C9. Chen, T., and Zhang, Y., "Three-Dimensional Modeling of Laser Sintering of a Two-

Component Metal Powder Layer on Top of Sintered Layers,” *Proceedings of 2005 ASME Summer Heat Transfer Conference*, San Francisco, CA, July 17-22, 2005

- C10. Chen, T., and Zhang, Y., 2005, “Thermal Modeling of Metal Powder-Based Selective Laser Sintering,” *Proceedings of 16th Solid Freeform Fabrication Symposium*, Austin, TX, Aug. 1-3, 2005.
- C11. Chen, T., and Zhang, Y., “Three-Dimensional Simulation of Multiple-Line Scan Laser Sintering of a Two-Component Metal Powder Layer on Top of Sintered Layers,” *Proceeding of 2005 International Mechanical Engineering Congress and Exposition*, Orlando, FL, Nov. 5-11, 2005.
- C12. Xiao, B., and Zhang, Y., “Numerical Simulation of Direct Metal Laser Sintering of Single-Component Powder on Top of Sintered Layers,” *Proceedings of 2006 International Mechanical Engineering Congress and Exposition*, Chicago, IL, Nov. 5-10, 2006.

7. Papers Submitted/to be Submitted to Referred Journals

- S1. Xiao, B., and Zhang, Y., “Numerical Simulation of Direct Metal Laser Sintering of Single-Component Powder on Top of Sintered Layers,” *ASME J. Manufacturing Science and Engineering*, 2007 (under review).
- S2. Shi, Y., Zhang, Y., and Konrad, C., “Solid-Liquid and Liquid-Vapor Phase Change Induced by a Nanosecond Laser in Selective Laser Sintering,” *Nanoscale and Microscale Thermophysical Engineering*, 2007 (under review).
- S3. Xiao, B., and Zhang, Y., “Laser Sintering of Metal Powders on Top of Sintered Layers under Multiple-Line Laser Scanning,” *Applied Physics A*, 2007 (to be submitted)
- S4. Damronglerd, P., and Zhang, Y., “Numerical Simulation of Melting and Solidification in Porous Structure using Temperature Transforming Model,” *Numerical Heat Transfer*, 2007 (to be submitted).
- S5. Damronglerd, P., and Zhang, Y., “Infiltration and Solidification of Liquid Metal into Laser Sintered Porous Structure,” 2007 (in preparation).

8. Expenditures

- FY06: 100%
- FY05: 100%
- FY04: 100%

9. Students Supported by ONR

- | | |
|----------------------------|-------------------------------------|
| 1. Mr. Chad Konrad | MS completed in July 2005 |
| 2. Dr. Tiebing Chen | Ph.D. completed in December, 2005 |
| 3. Dr. Bin Xiao | Ph.D. completed in December, 2006 |
| 4. Mr. Piyasak Damronglerd | Ph.D. to be completed in May, 2007. |

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14. ABSTRACT This project involves state-of-the-art, fundamental modeling of the laser beam-material interactions associated with Selective Laser Sintering (SLS) of single and multiple components powders. The research tasks carried out in the project include modeling of (1) coupling of laser beam and metal powders, (2) Liquid phase sintering of two-component metal powders, (3) Liquid phase sintering and Selective Laser Powder Remelting (SLPR) of single-component metal powders, and (4) the post-processing of the sintered parts with infiltration of liquid metal. The developed models are capable to handle any material combination, and can handle selective placement of different materials prior to laser scanning.						
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